Benefits of Non-Dimensionalization in Creation of Designs of Experiments for Sizing Torpedo Systems

Andrew P. Frits*, Kristen Reynolds†, Neil Weston‡, and Dimitri Mavris§
Aerospace Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

Non-dimensionalization is useful at many stages in the conceptual design process. One area of usefulness is in the creation and execution of Design of Experiments. A Design of Experiments that is run with dimensional quantities can often have a large number of failed or infeasible cases or require frustratingly small ranges on the design variables in order to execute cleanly. However, with the use of non-dimensional parameters in the Design of Experiments, the dimensional values being used in the analysis tool automatically scale themselves so that appropriate magnitudes of each parameter are always being used. This automatic scaling greatly increases the stability of Design of Experiments when non-dimensional parameters are used, limiting the number of failed cases. This paper explores potential non-dimensional parameters for use in the conceptual design of torpedo systems. The paper shows that traditional non-dimensional parameters used in propulsor design, such as advance ratio and thrust coefficient, also work well as torpedo design parameters. A short example is given where the performance of a Design of Experiments for a torpedo system is improved via the use of non-dimensional parameters.

Nomenclature

C_L	=	airfoil lift coefficient	L/D	=	fineness ratio
C_{Lmax}	=	maximum lift coefficient	M	=	mass
D_B	=	body diameter	n	=	rotations per second
Diam	=	body diameter	ρ	=	density of seawater
DoE	=	Design of Experiments	*RPM*	=	propulsor / shaft speed (rotations per minute)
F	=	force	T	=	time
HP	=	horsepower	T	=	thrust
J	=	advance coefficient	*TOAD*	=	Torpedo Optimization, Analysis, and Design Program
K_{HP}	=	thrust coefficient based on power	T_{SL}/W_{TO}	=	thrust-to-weight ratio
K_Q	=	torque coefficient	V_∞	=	velocity
K_T	=	thrust coefficient	W_{TO}/S	=	wing loading
L	=	length			

I. Introduction

NON-dimensionalization is a common practice in engineering fields, particularly aerospace. It is used to create automatically scaling parameters that can be used to represent a vehicle design independent of the vehicle's size. Non-dimensionalization is also a process that is useful when the physics of the problem are not fully

*Graduate Research Assistant, Aerospace Systems Design Laboratory
† Undergraduate Student, Aerospace Systems Design Laboratory
‡ Research Engineer II, Aerospace Systems Design Laboratory
§ Director, Aerospace Systems Design Laboratory, Boeing Prof.
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understood or overly complex. Essentially, by multiplying variables together until groups of like units are created, non-dimensional parameters are created. Furthermore, these non-dimensional parameters tend to be system drivers. These drivers are also crucial for proper scaling, a key to accurate preliminary design.

These non-dimensional parameters are useful in the running of Designs of Experiments (DoE). Designs of Experiments, constituting a "test or series of tests in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for change in the output response[1]," have become a common tool in conceptual design and multi-disciplinary optimization. They are often used in conjunction with response surface methodology to create meta-models, "whereby statistical models are built to approximate detailed computer analysis codes[2]". These statistical models typically take the form of polynomial approximations, thus slow-running analysis can be replaced by computationally un-intensive approximations[3,4,5]. Designs of Experiments work by intelligently sampling points in a design space, thus allowing a metamodel to be constructed that accurately reflects the design space, while only requiring a small number of actual analysis runs.

Unfortunately, when DoEs are run, points are typically chosen in the corners of the design space (see Figure 1). These corners of the design space are the regions that are the most likely to be non-convergent, or represent a design point for which the analysis code cannot find a feasible solution. If a DoE is used with dimensional quantities, picking corner points will often result in a worst-case selection of design variables. For instance, an aircraft example might involve the DoE selecting a low value for absolute thrust and a high value for payload. In such a case, the analysis program will return a bad result, such as zero for flight range, because the aircraft physically lacks the engine thrust required to takeoff. Unfortunately, attempting to circumvent this problem by keeping small variable ranges may overly truncate the desired design space. An alternative technique for handling failed points is to simply exclude the failed design points from the metamodel[3]. Both of these techniques have drawbacks. Reducing the variable ranges may artificially remove feasible design space in order to facilitate convergence at the corner points[6]. Excluding the non-convergent points also has drawbacks; if too many points are excluded the corresponding metamodel may not be accurate. In addition, the failed, or non-convergent points, may reflect a region of the design space where the physics of the problem is not feasible, so by excluding those points, yet including that region of the design space in the metamodel, the user will be inappropriately including infeasible design space as part of the metamodel. Additional possibilities for reducing or circumventing DoE modeling errors is through the use of alternative Designs of Experiments or metamodeling techniques, including latin hypercubes[7], Kriging metamodels[8,9], or neural networks[10,11].

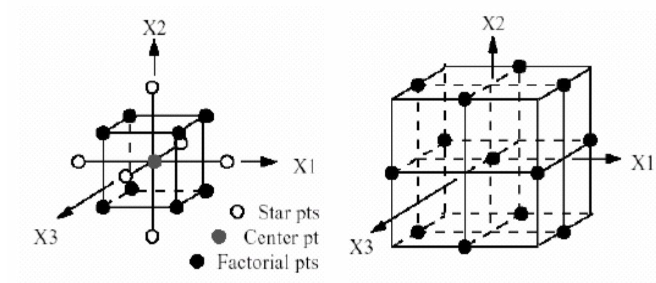

Figure 1. 3-Dimensional Representation of Designs of Experiments[7]

Another possibility in dealing with these situations is not to decrease variable ranges or exclude analysis points, but instead to choose smarter parameters for use in Designs of Experiments. This practice is already commonplace in conceptual design for aircraft. When sizing an aircraft, parameters such as thrust-to-weight ratio (T_{SL}/W_{TO}) are used instead of absolute thrust, and, correspondingly, wing loading (W_{TO}/S) is used instead of wing area. Thrust-to-weight ratio is non-dimensionalized, and, while wing loading has dimensions, it can still be considered a normalized parameter. The advantage of these parameters is that they automatically scale themselves with the vehicle. Thus, building upon the previous example, when using T_{SL}/W_{TO}, a larger vehicle will always have larger thrusts associated with it while a smaller vehicle will always be analyzed with correspondingly smaller thrusts. Therefore the thrust will always be of appropriate magnitude to correspond to each vehicle. Since the thrust is automatically scaling itself to appropriate magnitudes, a larger range of input variables can be used in the Design of Experiments.

Even though these techniques are common in aerospace, they are not yet common in the general aspects of torpedo design. One reason for the lack of use of these techniques in torpedo design is that, historically, torpedo diameter, one of the largest drivers for torpedo system performance, has been held fixed due to the requirement of maintaining compatibility with existing torpedo launch and handling systems, thus keeping one of the primary parameters for non-dimensionalization constant. However, with the approach of more revolutionary torpedo systems and un-manned undersea vehicles, the constraints on maximum diameter are now being relaxed so the designer once again has the freedom to choose an optimal weapon diameter.

This paper illustrates work in researching the potential benefits of normalization or non-dimensionalization of torpedo design parameters. The expected benefit from these techniques is to streamline the mechanism for preliminarily sizing torpedoes (similar to aircraft sizing techniques). In addition, common torpedo Designs of Experiments often generate many failed cases, resulting in unnecessarily small variable ranges and a multitude of excluded points. This unfortunate behavior in the DoE's can be attributed to the poor choice of parameters commonly used, generally dimensional quantities such as diameter, horsepower, shaftspeed (RPM), etc. Using intelligently chosen DoE parameters may significantly decrease the number of failed runs associated with these Designs of Experiments, allowing for the creation of more accurate, more useful metamodels, with variable ranges that better approximate real-world physics.

II. Torpedo Analysis

The analysis tool used for this study is the Torpedo Optimization, Analysis, and Design (TOAD) program, developed co-operatively between the Aerospace Systems Design Laboratory and the Naval Undersea Warfare Center, with additional collaboration from several other Navy entities. TOAD is an object-oriented, parametric sizing and synthesis program for both lightweight and heavyweight torpedo systems. It handles all-electric torpedoes, piston and turbine powered systems, and stored chemical-energy propulsion systems. It has been validated against existing torpedo systems[12] and used in research analysis comparing alternative torpedo concepts[13].

The inputs for the TOAD analysis program consist of physical torpedo quantities that are independent from the performance of the system. For instance, velocity and range are not inputs; instead, outer diameter, motor horsepower, and the length of the fuel section are inputs. A list of the inputs and outputs is shown in Figure 2. Because the torpedo is little more than a straight cylinder consisting of independently sized and constructed subsystems[14], a specific component's size can be specified by a single parameter, generally length. In this manner each subsystem can be defined regardless of its makeup. For instance, the amount of fuel that a torpedo carries can be specified by a single length value, regardless of the type of fuel present or whether batteries or liquid fuels are being used. A typical torpedo layout with individual sections is shown in Figure .

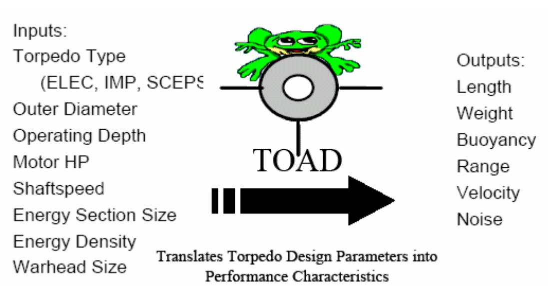

Figure 2. Inputs and Outputs for TOAD Analysis Tool[15]

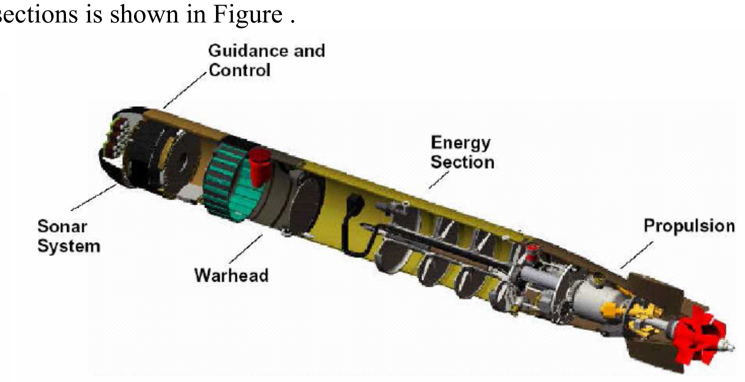

Figure 3. Typical Internal Layout of a Torpedo[16]

A. Iteration Process

The torpedo system is iteratively sized. The iterative sizing process is shown in Figure 4. To begin the iteration process, the front end of the torpedo, which includes the sonar, electronics, warhead, and fuel tank, is fixed at a specific size. This size is defined by the diameter of the torpedo and the individual section length inputs. The front-end of the torpedo is sized once and remains constant for the entirety of the iteration process. Next, the motor is sized based upon the input diameter, horsepower, and RPM. The propulsor is sized last, based upon the global diameter input, along with the RPM and the horsepower delivered by the motor. For this problem it is assumed that there is a direct drive shaft connecting the propulsor and the motor, thus both sub-systems have identical RPM values. The propulsor uses this data to calculate the power delivered, or the power transmitted into the water to propel the vehicle. These calculations are made using traditional blade/momentum theory for a two-element, ducted propulsor configuration[17]. Interactions between the propulsor and the torpedo, called the wake fraction and thrust deduction[18], are modeled with data from Mautner[19] and Burcher and Rydill[20].

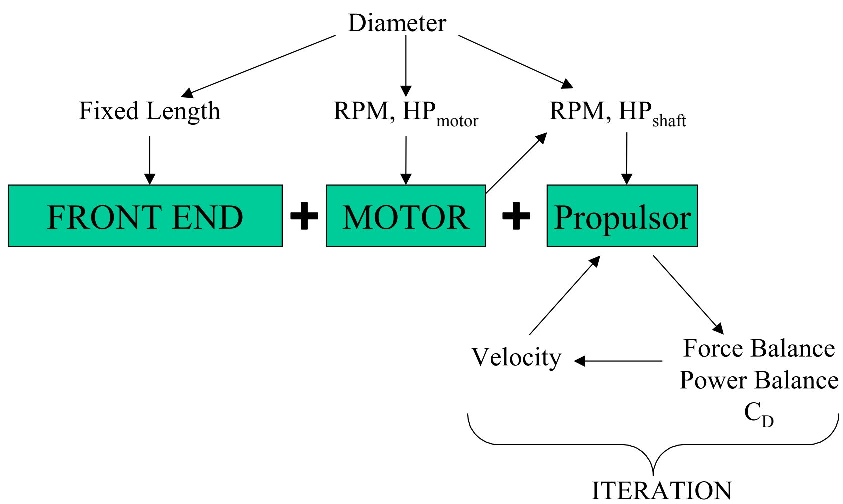

Figure 4. Layout of TOAD Iteration Procedure

Once the vehicle is initially sized, the vehicle drag coefficient is estimated. This estimation is based upon drag data found in references 21, 22, and 23. The final velocity of the vehicle is found by doing a force and power balance. The forces in the vertical direction: weight, buoyancy, and dynamic lift, must balance each other, as well as the forces in the horizontal direction: thrust, form drag, and induced drag. This force balance is displayed in Figure . Since the propulsor size is a function of the vehicle velocity, once a new vehicle velocity is determined, the propulsor must be sized again, following the iteration loop laid out in Figure 4.

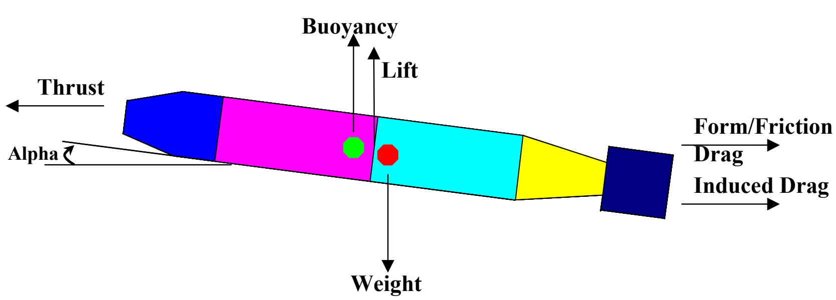

Figure 5. Force Balance for Torpedo Sizing

B. Failure Modes

A key element of this research is looking at regions of the design space for which valid torpedo designs cannot be created, otherwise known as the infeasible region of the design space. There are many mechanisms that drive torpedo designs to become infeasible. In the case of the TOAD torpedo design tool, most of the reasons for failure are found in the propulsor component of the torpedo. One such failure mechanism is when the torpedo propulsor cannot meet a C_{Lmax} constraint. The propulsor is essentially a rotating airfoil in the flow. The airfoil shape being used is a NACA 66 –mod(TMB) blade section, whose performance data can be found in Reference 24 and 25. The power (or thrust) delivered by the propulsor blade is proportional to the C_L of the airfoil and the square of its velocity relative to the flow. If a design situation occurs in which the C_L required to generate the required power is greater than the C_{Lmax} of the airfoil section, the propulsor is unable to deliver the required performance, and hits a C_{Lmax} constraint.

A second failure mode occurs when the torpedo begins to cavitate. Cavitation occurs when the decrease in the fluid pressure over various blade surfaces drops below the vapor pressure of the fluid. In this situation, pockets of gaseous water vapor develop, significantly lowering propulsor efficiency, creating large amounts of noise, and potentially damaging the propulsor.

A third failure occurs when the analysis program is unable to converge to a solution. This error often occurs when the force balance (Figure) cannot be resolved. Such a problem may occur when the torpedo does not have sufficient velocity and thus needs a larger engine, or if other propulsor modeling errors are driving the propulsor efficiency so low that the system cannot generate enough power.

A final failure mode develops from the historically based thrust deduction model being used. If the propulsor parameters of the torpedo lie outside of the validity of the model data, an error is reported. However, this error may not be a function of the physics, but simply the model data. If necessary, the model could be extrapolated into this region. For this paper, the data was extrapolated so that this region of the design space was still considered to be 'feasible'.

Table 1. Common Torpedo Failure Modes

Failure Mode	Relevant Torpedo Section	Reason	Solution
C_{LMax} Constraint Violation	Propulsor	Propulsor airfoil is unable to meet the required C_L	Decrease blade loading by decreasing power requirements, or increasing diameter or RPM
Cavitation Constraint Violation	Propulsor	Propulsor airfoil has too large of a pressure difference, dropping the static pressure below the fluid's vapor pressure	Increase Diameter
Unable to Converge	Propulsor / Torpedo	Propulsor is unable to provide enough power to resolve the torpedo force-balance May also be caused by other constraint violations	Increase motor power Prevent other constaint violations
Thrust Deduction Model Outside of Bounds	Propulsor	Propulsor is operating in a regime outside of the available database	Limit propulsor designs to within previous data, or extrapolate available data

The velocity, drag, and sizing calculations, along with more descriptions of the failure mechanisms, are more fully described in the TOAD User's Manual[12]. A summary of the torpedo inputs used for this analysis is given as Table 2.

Table 2. Inputs Used in the Analysis

Input	Units	Relevant Torpedo Section
Diameter	(in)	Front-End Motor Propulsor
Length	(in)	Front-End
RPM	(revs/min)	Motor Propulsor
HP	(hp)	Motor Propulsor

III. Formulation of DoE Parameters

Smart selection of potential Design of Experiments parameters is the first step in the implementation of this process. Traditionally used torpedo conceptual DoE parameters are often dimensional, non-normalized quantities, such as diameter, horsepower, propeller RPM, and internal sectional lengths (i.e., length of the fuel tank). Dimensional analysis techniques involve the creation of non-dimensional parameters from these quantities, through the comparison of units, as illustrated by the Buckingham-Pi theorem[26,27]. These techniques can be employed to develop better, more non-dimensional design parameters for torpedo Design of Experiments work.

When creating non-dimensional parameters for this analysis, it was desired to keep all of the parameter values as functions of the inputs into the TOAD analysis program, thus simplifying the execution of Designs of Experiments. Therefore, in creating these parameters, 'non-dimensionality' was sacrificed in order to retain parameters that were a function of the TOAD analysis inputs: diameter, RPM, and horsepower.

The first parameter to be explored is the relation between two large drivers on torpedo system performance: diameter and horsepower. Dimensional analysis was used to determine the relation between these two parameters. Using the following dimensions, time (T), length (L), force (F), and mass (M), along with the fact that power is energy per unit time, the following relations were constructed:

$$HP = \frac{L \cdot F}{T} = \frac{L \cdot \left(\frac{M \cdot L}{T^2} \right)}{T} = \frac{M \cdot L^2}{T^3} \tag{1}$$

Thus, horsepower can be related to length squared. Diameter, with units of length, is obviously proportional to length; therefore, horsepower should be proportional to the square of diameter, with units of mass over time cubed (Eq. 2).

$$HP \propto Diam^2, \frac{HP}{Diam^2} = \frac{M}{T^3} \tag{2}$$

Therefore, horsepower divided diameter squared makes sense as a potential design parameter, because it has decreased dimensionality. The parameter is clearly not non-dimensional, because it still retains units of mass over time, however it was desired to keep each parameter a function of only two variables, so that each parameter can be used to define a unique torpedo configuration. For example, if the parameters outer diameter and HP/Diam^2 were specified, a unique combination of HP and diameter would be defined. However, if the non-dimensional parameter were a function of three variables, say HP, diameter, and shaftspeed, then the system would not be uniquely defined.

Shaftspeed, or propulsor RPM, is another driving parameter that is addressed in this study. Propellers are often designed via the non-dimensional parameter called the advance coefficient[28]. The definition of advance coefficient is shown in Eq. (3).

$$J = \frac{V_\infty}{{}^{RPM}\!/_{60} \cdot Diam_B} \tag{3}$$

The propulsor advance ratio would be an excellent choice of design parameter; unfortunately, the design tool, TOAD, cannot be used with this advance ratio as an input parameter. The reason TOAD cannot use advance ratio is because the freestream velocity, V_∞, is an output to the analysis program, not an input. Since the freestream velocity is not known prior to running a case, it would be impossible to use the advance ratio to set a fixed value of RPM unless an additional iteration loop was created around the analysis program – something to be avoided if possible. For analysis tools with other input/output formats, advance coefficient would likely be a strong candidate as a choice for a DoE parameter. However, even though the advance coefficient is not workable as an input parameter for this analysis tool, it does give insight into the relationship between RPM and diameter. Advance ratio suggests that the formulation of the two parameters should be inversely proportional to each other, leading to the relationship in Eq. (4).

$$RPM \propto {}^{1}\!/_{Diam}, RPM \cdot Diam = \frac{L}{T} \tag{4}$$

This equation implies that RPM times diameter is an appropriate design parameter. Again, this parameter is not non-dimensional in nature, but should better capture the design trends than using RPM and diameter independently.

Yet another parameter of merit is the fineness ratio, defined as the length of the body divided by the width of the body, or the diameter. Fineness ratio is used in some aerospace fields, such as missile design[29], and is also associated with torpedo design. Two other common non-dimensional parameters used in Naval Engineering are based upon the thrust coefficient (K_T) and the torque coefficient (K_Q)[18]. Thrust coefficient is a parameter that non-dimensionalizes thrust. By using the relation that power is equal to thrust times velocity, the thrust coefficient can be written in terms of a power and hence renamed K_{HP}, as shown in Eq. (5), where n is rotations per second, D_B is the body diameter, and T is the thrust. Unfortunately, the thrust coefficient has the same drawback as advance ratio: it is a function of a response variable from the analysis tool, V_∞.

$$K_T = \frac{T}{\rho n^2 D_B^4}, K_{HP} = \frac{550 * HP}{V} \cdot \frac{1}{\rho n^2 D_B^4} \tag{5}$$

A form of the torque coefficient can be found by multiplying the thrust coefficient by the advance ratio, as shown in Eq. (6). This multiplication has the advantage that it removes velocity from the formulation, making torque coefficient useful because it is completely formulated from input parameters for the TOAD analysis program. Torque coefficient is therefore a true non-dimensional parameter that is solely a function of TOAD inputs. This fact gives the torque coefficient an advantage as a Design of Experiments parameter because it can be calculated before any TOAD runs are completed. These non-dimensional parameters have traditionally been used in Naval Architecture explicitly for propulsor design, but in this work their use is being expanded to include the entire undersea vehicle.

$$K_Q = K_T \cdot J = \frac{T}{\rho n^2 D_B^4} \cdot \frac{V}{nD_B} = \frac{HP}{V} \cdot \frac{1}{\rho n^2 D_B^4} \cdot \frac{V}{nD_B} = \frac{550 * HP}{\rho n^3 D_B^5} \tag{6}$$

In addition to using K_{HP} or K_Q directly, it may also be beneficial to simply look at the relations that they imply between horsepower and diameter: using simply HP/D^4 or HP/D^5 as design parameters. Table 3 summarizes the potential non-dimensional parameters that were identified.

Table 3. Potential Non-Dimensional Parameters

Non-Dimensional Parameter	Definition	Units
Advance Ratio	$J = \dfrac{V_\infty}{RPM/60 \cdot D_B}$	---
Thrust Coefficient	$K_{HP} = \dfrac{550 * HP}{V} \cdot \dfrac{1}{\rho n^2 D_B^4}$	---
Torque Coefficient	$K_Q = \dfrac{550 * HP}{\rho n^3 D_B^5}$	---
Fineness Ratio	L / D_B	---
---	HP / D_B^2	hp/in^2
---	HP / D_B^4	hp/in^4
---	HP / D_B^5	hp/in^5
---	$RPM \cdot D_B$	in/min

IV. Exploratory Research

The example problem being explored is a lightweight torpedo system, which traditionally has a diameter of 12 ¾ inches and a power of 200 HP or less[30,31]. The inputs and ranges that define the design space are given in Table 4. This example problem is challenging because the range of diameters available is quite large, from the short six inch torpedo to a medium-sized 14 inch torpedo. Additionally, the horsepower variation is also significant, from a lightly powered five horsepower to large 200 horsepower systems. These challenging ranges were used for a number of reasons. For one, the design space captures a wide range of possible torpedo configurations: from low-powered UUV's that could be deployed from a submarine's 6 ½ inch counter-measure dispensers, to high-powered, large diameter lightweight torpedoes (i.e., a 200 hp, 14 inch torpedo). Secondly, the design space is sufficiently large that regions of infeasibility will exist, thus giving the approach an opportunity to show its merit.

Table 4. Problem Design Variables and Ranges

Variable	Min	Max
Diameter (in)	6	14
Horsepower	5	200
RPM	2000	5000

Before looking at running advanced Designs of Experiments, a grid-search was used to explore the data. The grid search was done so that the complete design space could be viewed, clearly showing regions of constraint violations. A 32x32 fine grid was used in conjunction with diameter and horsepower, while a coarse grid with four levels run was for varying RPM. The final grid search therefore comprised 4,096 total points. Figure 6 shows the 2-dimensional results with RPM held constant at 2,000. Each point on the grid represents a single run, with varying markers used to indicate the pass/fail code returned by the analysis program. Black circles are used to indicate the feasible regions, with each failure mode having its own symbol. Separate, continuous fields of failure are illuminated in the graph. The border between these fields represents a constraint line for the given failure mode. In examining this figure, the large diameter, large horsepower trials, common to today's lightweight torpedoes, execute without failure, as expected. The medium diameter, lower horsepower runs are out of the range of the thrust deduction model. However, this failure is not associated with any boundary of physics, it simply means that the program is outside the range of validity for the analysis model. If it is assumed that model extrapolations are valid (a reasonable assumption for this paper), then this field of points can also be considered feasible. There are then two regions of infeasibility: the small diameter large horsepower systems are characterized by exceeding the C_{Lmax} required for the system, which eventually keeps the program from converging. On the opposite side, the very low horsepower (5 hp), large diameter systems fail to converge; this convergence failure is likely due to the analysis program's inability to complete a force balance for the torpedo.

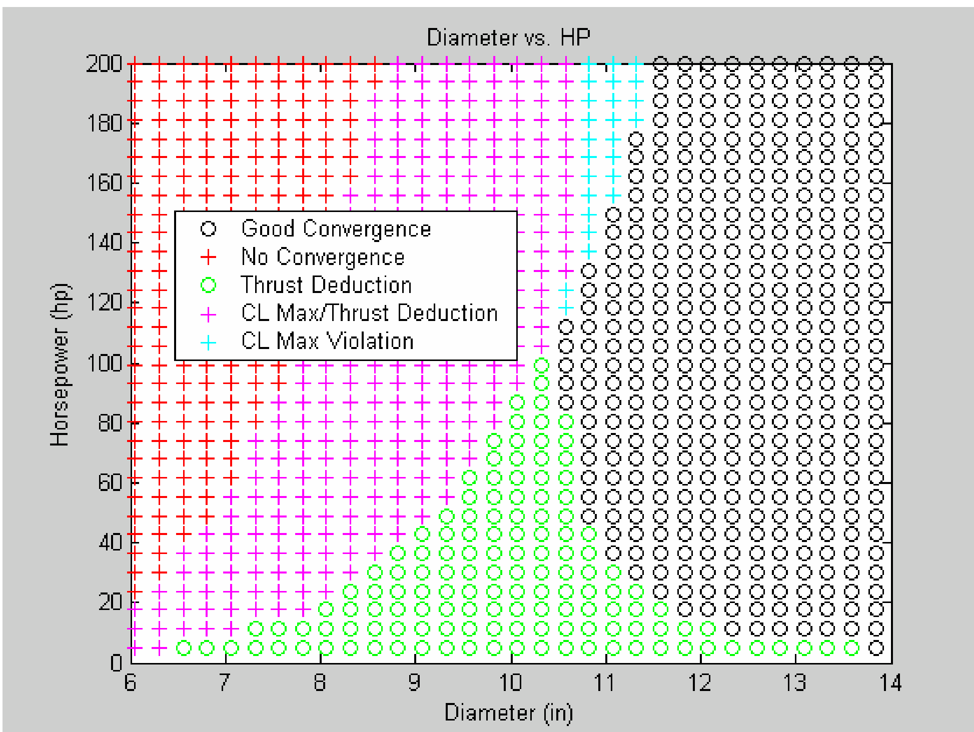

Figure 6. Grid Results Showing Constraints for Diameter and Horsepower, for RPM = 2000

Figure 7 shows the three-dimensional results for all the trial runs in the grid search. Variations in the constraints as a function of RPM can now be seen. At low values of RPM, there is a large region of constraint violations for the small diameter systems. But, at these low RPMs, the large diameter, low horsepower systems perform well. As the RPMs increase, the large diameter torpedoes begin to fail, while small diameter torpedoes perform progressively better.

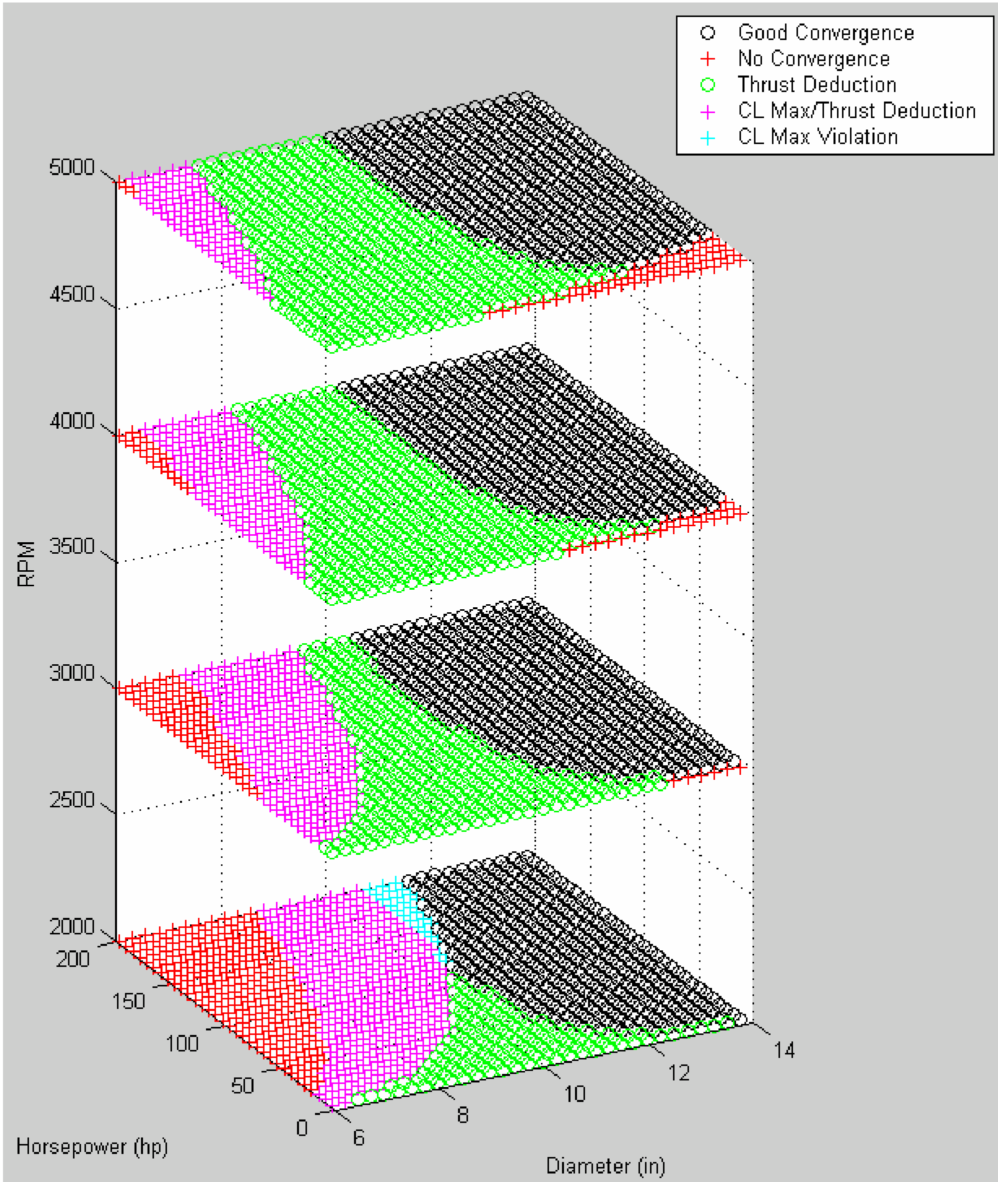

Figure 7. Grid Results Showing Constraints for Diameter, Horsepower, and RPM

The next step in the non-dimensionalization process is to begin examining the design space in terms of potential non-dimensional parameters. To do so, the previous grid search was transformed so that it was charted in terms of the potential non-dimensional parameters listed in Table 3. For the transformed plots, if discrete jumps exist between feasible and infeasible cases, then the parameter being plotted is a strong candidate for use in non-dimensionalization for Designs of Experiments. In these cases, the parameter can be used to determine whether a system is valid or invalid. If there is not a discrete jump between feasible and infeasible cases for a design parameter, then that parameter is a poor candidate for use in DoEs. Figure 8 shows some potential parameters: fineness ratio, diameter, and thrust and torque coefficients. The left-hand side of this figure shows thrust coefficient versus fineness ratio, or L/D. This figure shows a clean demarcation, or straight line, between feasible and infeasible points, indicating that K_{HP} and L/D could be used together to define a feasible model region. The right hand side of Figure 9 shows diameter and Torque Coefficient (K_Q). This figure shows that the diameter and torque coefficient can be used to clearly designate a line between feasible and infeasible design regions. Figure 9 shows how advance ratio is also useful as a DoE parameter.

System constraints in terms of these parameters are clearly visible as lines, illustrating the potential for creating engineering design rules for torpedoes from this information. For instance, from the thrust coefficient versus fineness ratio plot in Figure 8, the following design rule could be created:

$$\text{If } 5K_{HP} + L/D < 19, \text{the system is feasible} \tag{7}$$

It could also be possible to use these design rules to create a custom Design of Experiments, one specifically designed to remove infeasible or non-convergent regions from the valid design space. Reference 6 illustrates a method by which such constraint lines can be identified and custom DoEs created to exclude the non-convergent regions from the design space.

Figure 10 shows some plots that illustrate bad potential design parameters. The left hand side shows diameter versus horsepower over diameter squared, while the right hand side of this figure shows fineness ratio versus horsepower. The fineness ratio versus horsepower chart has no clean demarcation between feasible and infeasible regions. Instead, there is a large region of overlapping between feasible and infeasible cases. The diameter versus diameter over horsepower squared has similar overlap between cases. These parameters would therefore make poor choices for use in Designs of Experiments.

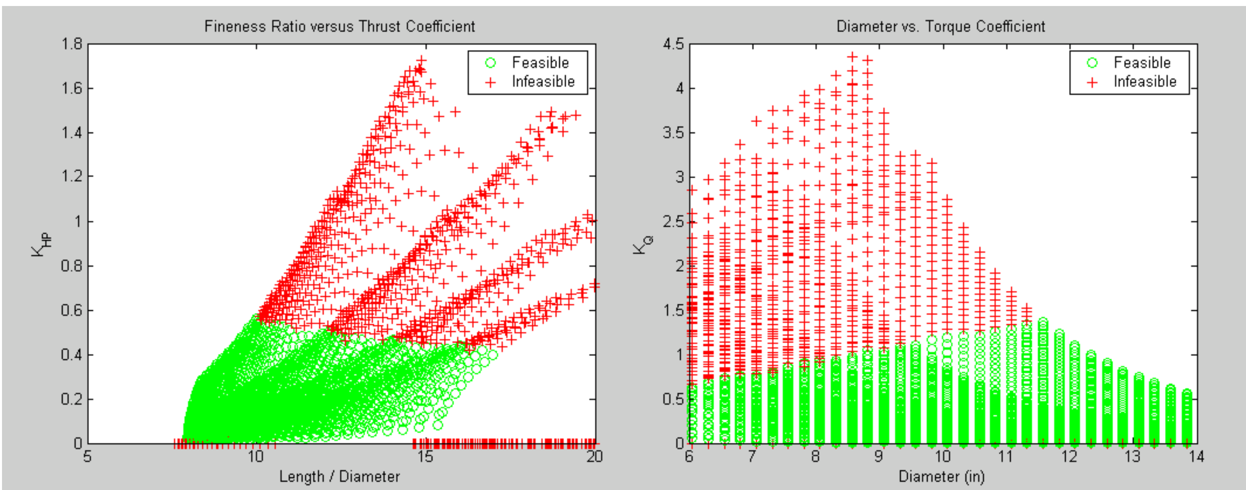

Figure 8. Illustration of Good Potential DoE Parameters

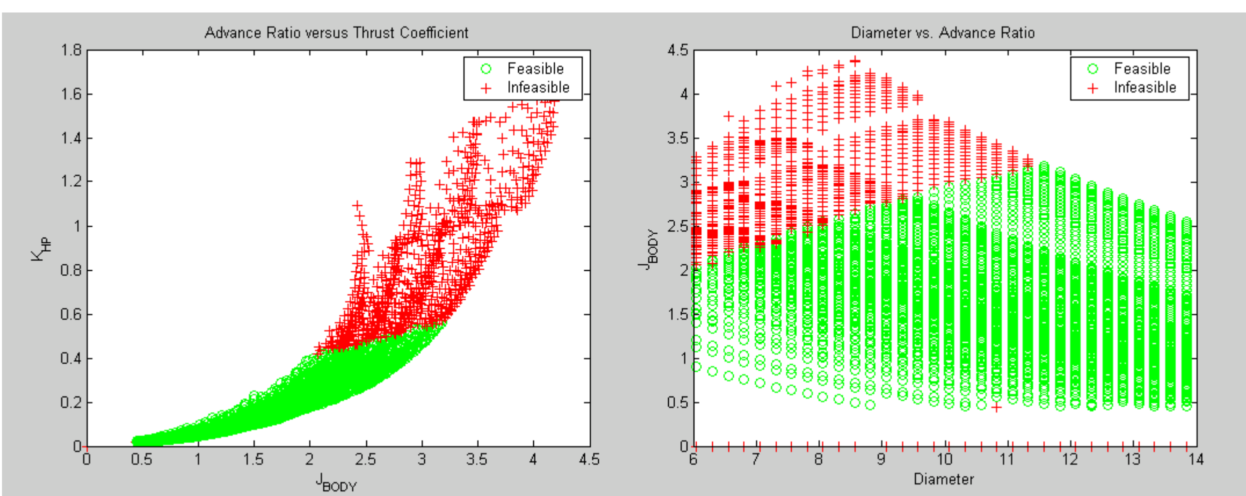

Figure 9. Additional Illustration of Good DoE Parameters

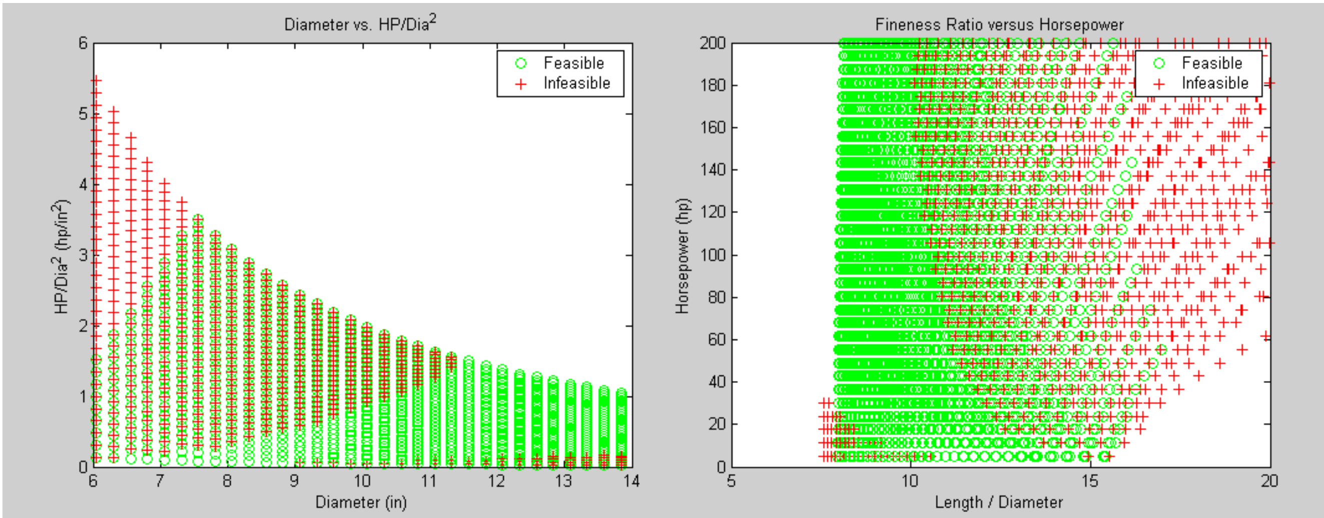

Figure 10. Illustration of Bad DoE Parameters

All the potential DoE parameters that were identified were tried against each other. Table 5 is a summary indicating which sets of parameters worked well together, and which sets performed poorly. Note that the dimensional parameters tended to do poorly. Likewise the 'derived' parameters, or only partially non-dimensionalized parameters such as horsepower over diameter squared, performed equally poorly, if not worse. It was the traditionally used, fully non-dimensional parameters, such as advance ratio, fineness ratio, thrust, and torque coefficients that performed exceptionally well. These parameters would be most effective to use in a Design of Experiments for torpedo systems.

Table 5. Summary of Results Comparing Potential Parameters for DoEs

		Dimensional Parameters			Partially Non-Dimensional Parameters				Non-Dimensional Parameters			
		Diameter	Horsepower	RPM	HP/Dia^2	HP/Dia^4	HP/Dia^5	RPM*Diameter	Fineness Ratio ($^L/_D$)	Advance Ratio (J)	Thrust Coefficient (K_{HP})	Torque Coefficient (KQ)
Dimensional Parameters	Diameter	---										
	Horsepower	B	---									
	RPM	B	B	---								
Partially Non-Dimensional Parameters	HP/Dia^2	B	B	B	---							
	HP/Dia^4	B	B	B	B	---						
	HP/Dia^5	B	B	B	B	B	---					
	RPM*Diameter	B	B	B	B	B	B	---				
Non-Dimensional Parameters	Fineness Ratio ($^L/_D$)	B	B	B	B	B	B	B	---			
	Advance Ratio (J)	**G**	B	B	B	B	B	B	**G**	---		
	Thrust Coefficient (K_{HP})	**G**	**G**	**G**	B	B	B	**G**	**G**	**G**	---	
	Torque Coefficient (KQ)	**G**	B	B	B	B	B	B	**G**	**G**	**G**	---

B = Bad
G = Good

V. Design of Experiments Results

The next step was to illustrate the use of these new design parameters in a Design of Experiments. Unfortunately, most of the parameters that performed well, such as fineness ratio, advance ratio, and thrust coefficient, are based upon responses from the TOAD analysis tool. These parameters use the overall vehicle length and the velocity of the vehicle in their calculations. Since TOAD treats these parameters as responses, they are difficult to implement as inputs into the analysis program. As such, it was decided to use the non-dimensional parameter for torque coefficient (K_Q) in the Design of Experiment, since this is the best-behaving parameter that is exclusively a function of the TOAD input variables.

It was decided to show the effects for a simple, two-dimensional Design of Experiments. To generate a baseline case, the dimensional design variables for diameter and horsepower were used from the example problem Table 4. These parameters were used in a three-level, full factorial experiment, for a total of 9 analysis runs. Of these 9 DoE runs, 3 of the parameter combinations failed: a 33% failure rate. Figure 11 shows a graphic of the design points and which cases failed in the analysis. A second full-factorial experiment was then run. However, instead of using diameter and horsepower as the DoE variables, diameter and torque coefficient were varied. The torque coefficient was varied from 0.02 to 0.5. This variation in K_Q resulted in a large range of horsepower, encompassing the entire range of original DoE values. The horsepower varied from less than 1.0 horsepower to nearly 500 horsepower. The original and new DoE values are compared to each other in Table 6. When running the nine cases of the new DoE, not a single failed case was reported. Thus, by running the DoE using the non-dimensional parameter for torque coefficient resulted in significantly better results than using the dimensional value of horsepower. This improvement in the Design of Experiments was obtained while still maintaining the entire original variable ranges; in fact, the variable ranges were increased for the non-dimensional case yet maintained superior performance. An overlay of the two Designs of Experiments is shown in Figure 11. The figure shows how the non-dimensional K_Q parameter steers the DoE away from the non-feasible portions of the design space while simultaneously retaining a large amount of the feasible design space. Therefore, the non-dimensional parameter K_Q can be used with good effect in removing infeasible design space from a Design of Experiments for conceptual torpedo design.

Table 6. Table Comparing Two Full-Factorial DoE's

	Old Parameters			**New Parameters**			
	Diameter	HP	Pass/Fail	Diameter	HP	KQ	Pass/Fail
Trial 1	6	5	P	6	0.28	0.02	P
Trial 2	6	102.5	**F**	6	3.67	0.26	P
Trial 3	6	200	**F**	6	7.06	0.50	P
Trial 4	10	5	P	10	3.63	0.02	P
Trial 5	10	102.5	P	10	47.23	0.26	P
Trial 6	10	200	P	10	90.83	0.50	P
Trial 7	14	5	**F**	14	19.54	0.02	P
Trial 8	14	102.5	P	14	254.03	0.26	P
Trial 9	14	200	P	14	488.52	0.50	P
		Pass Rate:	**66%**			**Pass Rate:**	**100%**

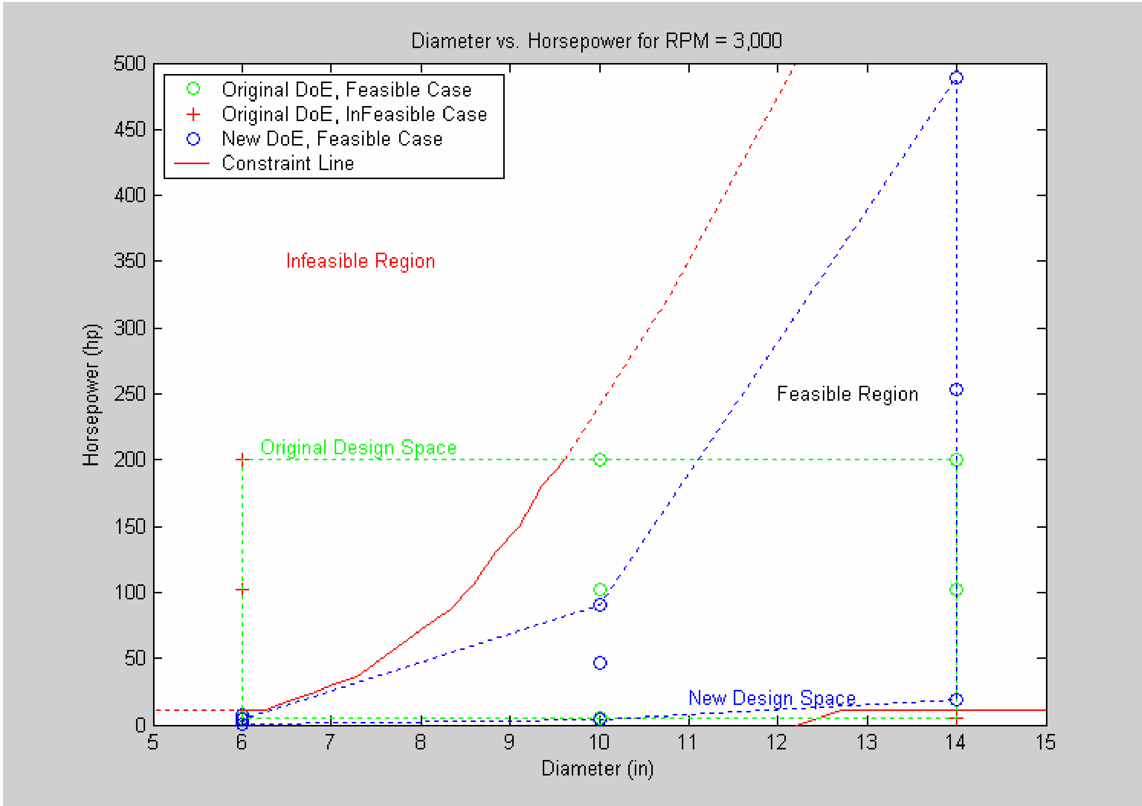

Figure 11. Comparison of Original Design of Experiments to New DoE

VI. Conclusions

In transforming the results of the grid search to various potential non-dimensional parameters, clear demarcations become visible that showed which sets of parameters could be used to determine whether a design would be feasible or infeasible. These plots showed that the best parameters for use in a Design of Experiments of torpedo systems are the fully non-dimensional parameters, similar to those already used in engineering disciplines, such as fineness ratio, advance ratio, thrust coefficient, and torque coefficient. When possible, sizing and synthesis programs for torpedoes should be written so that the inputs can be formulated so that they are in terms of these non-dimensional parameters.

In addition to illustrating strong non-dimensional parameters, the results show that definite constraint equations can be written in terms of these non-dimensional parameters. These equations could be used to create engineering rules of thumb for the system or could be used in the creation of custom Design of Experiments that avoids infeasible regions of the design space.

Finally, a quick example employing a Design of Experiments showed that this smart selection of design parameters could significantly reduce or even eliminate the infeasible cases from the Design of Experiments, all while still maintaining an aggressive range for the design variables. Non-dimensionalization should be considered before any large Design of Experiments study is conducted.

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